Prediction of channel information in multi-user OFDM systems

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***Abstract*—Channel information is indispensable to employ advanced channel aware technologies such as packet scheduling and adaptive modulation and coding (AMC). In this paper, we first investigate the delay effect of instantaneous signal to interference and noise power ratio (SINR) on the spectral efficiency of multi-user orthogonal frequency division multiplexing (OFDM) systems that employ packet-based channel aware technologies. To alleviate the performance degradation due to delayed channel information, we consider the use of predicted channel gain for link adaptation with packet scheduling. It is shown that the use of predicted channel gain can significantly enhance the spectral efficiency particularly in high mobility environments. For practical realization of an optimum predictor, we propose a grouped minimum mean square error (MMSE) prediction scheme, which can substantially reduce the implementation complexity without noticeable performance degradation. Finally, the proposed scheme is verified by computer simulation.**

Index terms: channel state information, packet scheduling, MMSE prediction, OFDM

I. INTRODUCTION

It is known that channel aware techniques (e.g., packet scheduling, adaptive modulation and coding (AMC), and hybrid automatic repeat request (HARQ)) can significantly enhance the average spectral efficiency of multi-user orthogonal frequency division multiplexing (OFDM) systems [1, 2]. However, these channel aware techniques needs accurate channel state information (CSI) (e.g., instantaneous signal to interference and noise power ratio (SINR)) in the transmitter. Previous studies often assume the use of perfect (or accurate) CSI in the transmitter [3, 4]. However, since the transmitter often acquires the CSI from the receiver, it may suffer from performance degradation due to unavoidable transmission delay through a feedback channel. This problem becomes serious as the mobility increases. To alleviate this problem, the use of predicted CSI was suggested [5].

Recently, several researchers have investigated the effect of channel (or instantaneous SINR) prediction on the link-adaptation in single-user systems [6, 7]. However, to the author's best knowledge, no result has been reported on the effect of instantaneous SINR prediction on multi-user systems. In this paper, we consider the use of predicted channel gain (or instantaneous SINR) for link-adaptation with packet scheduling in the downlink of a multi-user OFDM system. To this end, we consider the use of a linear optimum minimum mean square error (MMSE) predictor, called Wiener predictor, as the channel gain predictor. Although the optimum Wiener predictor can provide appropriate performance even in high mobility condition, it may not easily be applicable due to high implementation complexity [8]. To alleviate this problem, we employ a grouped MMSE filtering scheme that can substantially reduce the implementation complexity without noticeable performance degradation.

The paper is organized as follows. Section II describes a multi-user OFDM downlink system. In Section III, we investigate the effect of channel prediction on the channel-aware techniques. To alleviate the implementation complexity problem, we propose a grouped MMSE filtering scheme in Section IV. Finally, conclusions are summarized in Section V.

II. SYSTEM FRAMEWORK

A. System model

Consider an OFDM downlink system, where $X_m(n,k)$ denotes the m–th user signal at the n–th symbol time and the k-th subcarrier, $m \in \{0,1,\cdots,M-1\}$ and $k \in \{0,1,\cdots,K-1\}$. The frequency domain symbol is converted into a time domain signal using inverse fast Fourier transform (FFT). A cyclic prefix (CP) is inserted to preserve the orthogonality between the subcarriers and to eliminate the interference between the adjacent OFDM symbols. We assume that each data packet comprises N_t OFDM symbols in the time domain and N_f subcarriers in the frequency domain, and that pilot symbols are regularly inserted in a rectangular pattern (i.e., apart by d_t and d_f symbols in the time and frequency grid, respectively).

After the FFT in receiver, the signal of user m_Q selected by the packet scheduler can be represented by

$$Y_{m_Q}(n,k) = H_{m_Q}(n,k) X_{m_Q}(n,k) + Z_{m_Q}(n,k)\,, \qquad (1)$$

where $X_{m_Q}(n,k)$ is the data signal, $H_{m_Q}(n,k)$ is the frequency response of channel impulse response (CIR) from the transmitter to a selected user m_Q , and $Z_{m_Q}(n,k)$ is the background noise plus interference term which can be approximated as zero mean additive white Gaussian noise (AWGN) with variance $\sigma^2_{m_Q,Z}$. Here, the CIR can be represented as

$$h_{m_Q}(t,\tau) = \sum_{l=0}^{L_{m_Q}-1} h_{m_Q,l}(t)\delta(\tau - \tau_{m_Q,l}) , \tag{2}$$

where L is the number of multipaths, $\delta(\cdot)$ is Kronecker delta function, $\tau_{m_Q,l}$ and $h_{m_Q,l}(t)$ are the delay and complex-valued CIR at time t of the l-th path, respectively. Since the CIR can be estimated accurately by using the received pilot symbols, we assume perfect coherent detection in the receiver.

B. Packet scheduling

The spectral efficiency can significantly be improved by employing an intelligent packet scheduling scheme taking the channel condition into account, so-called opportunistic packet scheduling [9-11]. The maximum SINR scheduling and proportional fair (PF) scheduling are examples of the opportunistic scheduling.

The maximum SINR scheduling selects a user whose instantaneous SINR is the largest as

$$m_Q = \underset{m\in\{1,\cdots,M\}}{\arg}\max\left[\bar{\gamma}_m \gamma_m(n,k)\right], \tag{3}$$

where $\bar{\gamma}_m$ and $\gamma_m(n,k)\left(=|H_m(n,k)|^2\right)$ are the average SINR and the channel gain of user m, respectively. Thus, $\bar{\gamma}_m\gamma_m(n,k)$ represents the instantaneous SINR. Assuming that M users are allocated in each subcarrier, we can omit the subcarrier index k without loss of generality. This implies that a multi-carrier system with an opportunistic scheduler can be treated as a simple parallel extension of a single-carrier time division multiplexing system [9]. Therefore, we will omit the index k in what follows.

The maximum SINR scheduling maximizes the spectral efficiency by achieving the multi-user diversity (MUD) gain. However, it may not guarantee fairness if the average SINR $\bar{\gamma}_m$ of each user has a large variation. This fairness problem can be alleviated by employing a PF scheduling scheme as in the cdma1x EvDO system [10]. Letting $R_m(n)$ be a possible transmission data rate at symbol time n and $\bar{R}_i(n)$ be the average data rate up to the symbol time n, the PF scheduler selects a user according to

$$m_Q = \underset{m\in\{1,\cdots,M\}}{\arg}\max\left[\frac{R_m(n)}{\bar{R}_m(n)}\right]. \tag{4}$$

If we assume that all the users experience the same channel statistics and that the observation time is sufficiently long, (4) can be described as [11]

$$m_Q = \underset{m\in\{1,\cdots,M\}}{\arg}\max\left[\frac{\bar{\gamma}_m\gamma_m(n)}{\bar{\gamma}_m}\right] = \underset{m\in\{1,\cdots,M\}}{\arg}\max\left[\gamma_m(n)\right] \tag{5}$$

C. Prediction of instantaneous SINR

Accurate channel information is indispensable for the employment of channel aware techniques. The CIR of user m corresponding to the pilot symbol can be estimated by a maximum likelihood (ML) method as

$$\begin{aligned}\tilde{H}_m(nd_t,kd_f) &= Y_m(nd_t,kd_f)/X_m(nd_t,kd_f)\\ &= H_m(nd_t,kd_f)+\tilde{Z}_m(nd_t,kd_f)\end{aligned}, \tag{6}$$

where $\tilde{Z}_m(nd_t,kd_f)$ denotes the noise term.

To alleviate the delay problem associated with the CSI, we consider the prediction of channel gain at time $(n+p)d_t$. The predicted channel gain can be obtained using a conventional one-dimensional Wiener predictor in the time domain as

$$\hat{H}_m\left((n+p)d_t\right) = \mathbf{w}_o^H\tilde{\mathbf{H}}_m , \tag{7}$$

where $\tilde{\mathbf{H}}_m = [\tilde{H}_m(nd_t)\ \tilde{H}_m\left((n-1)d_t\right)\cdots\tilde{H}_m\left((n-U+1)d_t\right)]^T$ denotes U memoryless ML estimates of the pilot symbol, the superscript H and T respectively denote the Hermitian and transpose operation, and $\mathbf{w}_o$ is the Wiener filter coefficient determined as

$$\mathbf{w}_o = \mathbf{R}^{-1}\mathbf{p} . \tag{8}$$

Here, $\mathbf{R}\left(=E[\tilde{\mathbf{H}}\tilde{\mathbf{H}}^H]\right)$ is the $\left(U\times U\right)$ auto-covariance matrix of the received pilot symbol and $\mathbf{p}\left(=E[\tilde{\mathbf{H}}H^*\left((n+p)d_t\right)]\right)$ is the $\left(U\times 1\right)$ cross-covariance vector of the desired and the received pilot symbol. Then, the corresponding prediction MSE can be represented as

$$\begin{aligned}\sigma_e^2 &= \sigma_d^2 - \mathbf{w}_o^H\mathbf{p} - \mathbf{p}^H\mathbf{w}_o + \mathbf{w}_o^H\mathbf{R}\mathbf{w}_o\\ &= \sigma_d^2 - \mathbf{p}^H\mathbf{w}_o\end{aligned} \tag{9}$$

where $\sigma_d^2 = E[|H\left((n+p)d_t\right)|^2]$.

The instantaneous SINR can easily be predicted from the predicted channel gain. Since the average SINR can be estimated accurately by a long term average [11], we can assume that the average SINR $\bar{\gamma}_m$ can be estimated very accurately. The instantaneous SINR at time $(n+p)d_t$ can be predicted as

$$\hat{\gamma}_m\left((n+p)d_t\right)\bar{\gamma}_m = |\hat{H}_m\left((n+p)d_t\right)|^2\,\bar{\gamma}_m . \tag{10}$$

III. LINK ADAPTATION WITH PEDICTED SINR

The average spectral efficiency can be represented as [12]

$$\bar{\Lambda}_m = E[\Lambda_m] = E[\log_2(1+\eta\bar{\gamma}_m\gamma_m)] \tag{11}$$

where Λ_m denotes the instantaneous spectral efficiency and η denotes a system loss factor due to implementation. For ease of analysis, we assume that all the users experience the same average SINR (i.e., $\bar{\gamma}_m = \bar{\gamma}$). Let Γ_r^M be the r-th element of the channel gain vector $\boldsymbol{\gamma}_{OS}$, arranged in an ascending order, given by

$$\Gamma_r^M = OS_r^M\{\gamma_1, \gamma_2, \cdots, \gamma_M\}\ , \tag{12}$$

where $OS_r^M\{\gamma_1, \gamma_2, \cdots, \gamma_M\}$ denotes the output of an order statistic filter with rank *r*. As a special case, it can be seen that $\Gamma_M^M = \max_{i=\{1,\cdots,M\}} \gamma_i$. Then, the cumulative distribution function (cdf) and probability density function (pdf) of Γ_r^M are respectively represented as [13]

$$\begin{aligned} F_{\Gamma_r^M}(x) &= \sum_{i=r}^{M} \binom{M}{i} F_\gamma^k(x)\{1 - F_\gamma(x)\}^{M-i} \\ f_{\Gamma_r^M}(x) &= r\binom{M}{r} F_\gamma^{r-1}(x)\{1 - F_\gamma(x)\}^{M-r} f_\gamma(x) \end{aligned} \tag{13}$$

where $f_\gamma(x)$ and $F_\gamma(x)$ denote the pdf and cdf of the channel gain γ , respectively. Here, we omit the time index *n* and the user index *m* for brevity. Note that the user selected by a PF scheduler is equal to Γ_M^M .

When the outdated channel gain is used for the PF scheduling, the average spectral efficiency can be represented in a closed form [9]. Similarly, we can analyze the performance of PF scheduling with the use of predicted channel gain. Assuming that user $\hat{m}_Q$ is scheduled based on the predicted channel gain, we can represent the average spectral efficiency of the selected user as

$$E[\Lambda_{\hat{m}_Q}] = E\left[\log_2\left\{1 + \eta\bar{\gamma}\,\gamma_{\hat{m}_Q}\left((n+p)d_t\right)\right\}\right], \tag{14}$$

where $\gamma_{\hat{m}_Q}\left((n+p)d_t\right) = |H_{\hat{m}_Q}\left((n+p)d_t\right)|^2$.

The CIR at time $(n+p)d_t$ can be predicted using a Wiener predictor as

$$\hat{H}_{\hat{m}_Q}\left((n+p)d_t\right) = H_{\hat{m}_Q}\left((n+p)d_t\right) + e_{\hat{m}_Q}\left((n+p)d_t\right) \tag{15}$$

where $e_{\hat{m}_Q}\left((n+p)d_t\right)$ denotes the prediction error. For simplicity of description, we will omit the time index *n* and pilot interval d_t in what follows. From [10]

$$\begin{aligned} E[H_{\hat{m}_Q}(p) e_{\hat{m}_Q}^*(p)] &= \sigma_e^2 \\ E[\hat{H}_{\hat{m}_Q}(p) H_{\hat{m}_Q}^*(p)] &= 1 - \sigma_e^2 \end{aligned} \tag{16}$$

$H_{\hat{m}_Q}(p)$ in (16) can be represented as

$$H_{\hat{m}_Q}(p) = \hat{H}_{\hat{m}_Q}(p) + \sigma_e z(p) \tag{17}$$

where σ_e^2 denotes the variance of the prediction error $e_m(p)$, and $\hat{H}_{\hat{m}_Q}(p)$ and $z(p)$ are independent zero-mean complex Gaussian random variables with unit variance. Thus, the channel gain of the scheduled user can be represented as

$$\gamma_{\hat{m}_Q}(p) = \hat{\gamma}_{\hat{m}_Q}(p) + \sigma_e^2 |z(p)|^2 + 2\,\mathrm{Re}\{\hat{H}_{\hat{m}_Q}(p) z^*(p)\} \tag{18}$$

where $\gamma_{\hat{m}_Q}(p) = |H_{\hat{m}_Q}(p)|^2$ and $\hat{\gamma}_{\hat{m}_Q}(p) = |\hat{H}_{\hat{m}_Q}(p)|^2$.

Since the CIR is modeled as a zero mean complex Gaussian random variable, the predicted channel gain $\hat{\gamma}_{\hat{m}_Q}(p)$ can be modeled as an independent exponential random variable with pdf given by

$$f_{\hat{\gamma}}(x) = \frac{e^{-x/(1-\sigma_e^2)}}{1 - \sigma_e^2}\ . \tag{19}$$

After the scheduling with the order statistic filtering in (12), the pdf of $\hat{\gamma}_{\hat{m}_Q}(p)$ can be written as

$$f_{\hat{\gamma}_{\hat{m}_Q}}(x) = M\{F_{\hat{\gamma}}(x)\}^{M-1} f_{\hat{\gamma}}(x)\ . \tag{20}$$

Neglecting the last term in (18), we can approximate (20) as [9]

$$f_{\gamma_{\hat{m}_Q}}(x) \approx M \sum_{i=0}^{M-1} \binom{N-1}{i} (-1)^i \frac{e^{-x/\sigma_e^2} - e^{-x(i+1)/(1-\sigma_e^2)}}{1 + i\sigma_e^2 - 2(1-\sigma_e^2)}\ . \tag{21}$$

Thus, the average spectral efficiency with the use of predicted channel gain can be represented as

$$\begin{aligned} \bar{\Lambda}_p &= E[\log_2(1 + \eta\bar{\gamma}\,\gamma_{\hat{m}_Q})] \\ &\approx \frac{M}{\log 2} \sum_{i=0}^{M-1} \binom{M-1}{i} (-1)^i \frac{\sigma_e^2 e^{1/\sigma_e^2\eta\bar{\gamma}}\,\mathrm{Ei}(1/(1-\rho^2)\eta\bar{\gamma}) - \frac{1-\sigma_e^2}{i+1} e^{(i+1)/(1-\sigma_e^2)\eta\bar{\gamma}}\,\mathrm{Ei}(\frac{(i+1)}{(1-\sigma_e^2)\eta\bar{\gamma}})}{1 + i\sigma_e^2 - 2(1-\sigma_e^2)} \end{aligned} \tag{22}$$

where $\mathrm{Ei}(x) = \int_x^\infty \frac{e^{-t}}{t} dt$.

To verify the result, the performance of average spectral efficiency is evaluated by computer simulation in terms of the normalized delay $f_d T_s p d_t$. When the performance loss factor η and average SINR are -5dB and 8dB, respectively, Fig.1 depicts the average spectral efficiency with the use of predicted channel gain, where the legend ‘21×1’ denotes the tap size of the Wiener filter. The simulation parameters are summarized in Table 1, where we assume that the channel is unchanged during each packet time. For comparison, the performance with the use of non-predicted channel gain is depicted as ‘No prediction’. For reference, the prediction MSE is also depicted. It can be seen that the use of predicted gain is quite effective in the presence of high mobility and that the analytic results agree well with the simulation results.

Although (23) is represented in a closed form, it is not easily calculated. Instead, we consider an upper bound of (23) using Jensen’s inequality and concaveness of the logarithm function. Assuming no feedback delay (i.e., ideal case), the average spectral efficiency is bounded as [9]

$$\begin{aligned} \bar{\Lambda}_{ideal} &= E\left[\log_2\left\{1 + \eta\bar{\gamma}\,\gamma_{m_Q}(0)\right\}\right] \\ &\le \log_2\left\{1 + \eta\bar{\gamma}\,E[\gamma_{m_Q}(0)]\right\} \\ &= \log_2\left\{1 + \eta\bar{\gamma}\left(1 + \sum_{i=2}^{M} \frac{1}{i}\right)\right\} \end{aligned} \tag{23}$$

where $E[\gamma_{m_Q}(0)] = \Gamma_M^M$. Note that the second term $\sum_{i=2}^{M} 1/i$ represents the multi-user diversity (MUD) gain achieved in the ideal condition.

Assuming the use of channel gain without prediction, the CIR at the service time can be represented as

$$H_{m_Q}(p) = \rho H_{m_Q}(0) + \sqrt{1-\rho^2}\, z_{m_Q} \tag{24}$$

where z_{m_Q} and $H_{m_Q}(0)$ respectively denote zero mean complex Gaussian random variables with unit variance, and $\rho = E[H_{m_Q}(0)H^*_{m_Q}(p)] \le 1$. The expected channel gain at time $(n+p)d_t$ can be represented as

$$E[\gamma_{m_Q}(p)] = \rho^2 E[\gamma_{m_Q}(0)] + (1-\rho^2) = \rho^2(1+\sum_{i=2}^{M}\frac{1}{i}) + (1-\rho^2)\ . \quad (25)$$

Thus, it can be shown that the corresponding spectral efficiency is bounded as

$$\begin{aligned}\bar{\Lambda}_{np} &\le \log_2\left\{1+\eta\bar{\gamma}\, E[\gamma_{m_Q}(p)]\right\} \\ &= \log_2\left\{1+\eta\bar{\gamma}\left(1+\rho^2\sum_{i=2}^{N}1/i\right)\right\}\end{aligned} \quad (26)$$

Since

$$\begin{aligned}E[\gamma_{\hat{m}_Q}(p)] &= E[\hat{\gamma}_{\hat{m}_Q}(p) + \sigma_e^2\,|\,z(p)|^2 + 2\,\mathrm{Re}\{\hat{H}_{\hat{m}_Q}(p)z^*(p)\}] \\ &= (1-\sigma_e^2)\sum_{i=1}^{M}1/i + \sigma_e^2,\end{aligned} \quad (27)$$

it can be shown that

$$\begin{aligned}\bar{\Lambda}_{p} &\le \log_2\left\{1+\eta\bar{\gamma}\, E[\gamma_{\hat{m}_Q}(p)]\right\} \\ &= \log_2\left\{1+\eta\bar{\gamma}\left(1+(1-\sigma_e^2)\sum_{i=2}^{M}\frac{1}{i}\right)\right\}\end{aligned} \quad (28)$$

Compared to (23), (26) suggests that the MUD gain is affected by a factor of ρ^2 when the scheduling is performed based on the predicted channel gain. If the channel correlation ρ is zero, no MUD gain is achievable. On the other hand, (28) suggests that the MUD gain is affected by a factor of $(1-\sigma_e^2)$ with the use of predicted channel gain, where $0 \le \sigma_e^2 \le 1$. It can be seen in Fig. 1 that ρ^2 rapidly decreases as the mobility increases, whereas $(1-\sigma_e^2)$ does not.

Fig. 2 depicts the average spectral efficiency in terms of the prediction MSE. For reference, the spectral efficiency is also shown when there is no MUD gain. It can be seen that the use of predicted channel gain is quite effective unless the prediction inaccuracy is too large. Notice that no MUD gain is achievable if the prediction MSE σ_e^2 is larger than 1 as mentioned before.

IV. A COMPLEXITY REDUCED CHANNEL PREDICTOR

The use of predicted channel gain can significantly improve the performance of cannel aware techniques. However, the use of a Wiener type predictor may not easily be applicable mainly due to the implementation complexity [8, 11]. To alleviate this complexity problem, it is often considered the use of a simple moving average (MA) or Lagrange interpolation filter as the predictor. However, these filters may not provide desired performance because they do not efficiently utilize the channel correlation properties [11]. To alleviate these issues, we propose a so-called grouped MMSE filtering technique. If the filter coefficients are not much changed between the adjacent pilot symbols, it can be possible for the filtering process to use adjacent pilot symbols in a group basis rather than a symbol by symbol basis.

As illustrated in Fig. 3, G consecutive pilot symbols are combined for the grouped MMSE prediction of order U, where $\tilde{H}'(u)$ denotes the sum of CIR estimates corresponding to G pilot symbol, represented as

$$\tilde{H}'(u) = \sum_{i=0}^{G-1}\tilde{H}(uG-i) = \mathbf{w}_1\tilde{\mathbf{H}}_{uG},\ \ u = 0,-1,-2,\cdots,-U+1\,, \quad (29)$$

where $\mathbf{w}_1$ denotes a $(1\times U)$ unitary vector and $\tilde{\mathbf{H}}_{uG} = [\tilde{H}(uG)\cdots\tilde{H}(uG-G+1)]^T$. Letting $\tilde{\mathbf{H}}' = [\tilde{H}'(0)\cdots\tilde{H}'(-U+1)]^T$, the optimum coefficient of this grouped MMSE filter can be represented as

$$\mathbf{w}'_o = (\mathbf{R}')^{-1}\mathbf{p}' = [w'_0\ w'_{-1}\ \cdots\ w'_{-U+1}]^T \quad (30)$$

where $\mathbf{R}'\left(= E[\tilde{\mathbf{H}}'\tilde{\mathbf{H}}'^H]\right)$ and $\mathbf{p}'\left(= E[\tilde{\mathbf{H}}'H^*(p)]\right)$ respectively represent the auto-covariance matrix and the cross-covariance vector of the grouped MMSE filter. Then, the channel can be predicted as

$$\hat{H}(p) = (\mathbf{w}'_o)^H\tilde{\mathbf{H}}' \quad (31)$$

and the corresponding prediction MSE is given by $\sigma_e'^2 = \sigma_d^2 - \mathbf{p}'^H\mathbf{w}'_o$.

In order to properly employ the proposed groped prediction technique, it is necessary to determine the number G considering the channel correlation between the pilot symbols. We combine the pilot symbols in a group, whose correlation values are larger than a threshold level λ. Simulation results show that the optimum threshold is in a range of 0.95 to 0.99. Although the optimum correlation threshold somewhat decreases as the maximum Doppler frequency increases, it may be practical to use a constant threshold (e.g., λ=0.95).

To evaluate the performance of the proposed prediction scheme, Fig. 4 depicts the average spectral efficiency in terms of the normalized group delay when the proposed grouped MMSE predictor is employed with λ=0.95. For comparison, the performance of the Wiener prediction with U=5 and 51 is also depicted. It can be seen that the proposed scheme is quite effective in high mobility environments and that it provides near optimum performance compared to the use of Wiener predictors. The computational complexity is also compared in Table 2, where the sample correlation indicates whether the channel correlation is calculated based on a symbol-by-symbol or grouped-symbol basis. It can be seen that the proposed scheme significantly reduces the implementation complexity compared to the Wiener filters.

V. CONCLUSION

In this paper, we have considered the use of predicted channel gain for the employment of channel-aware techniques in multi-user OFDM systems. When a Wiener-type optimum predictor is applied to the prediction of channel gain, the performance of PF scheduling is analyzed and verified by computer simulation. It has been shown that the use of predicted channel gain can significantly enhance the performance of channel-aware techniques in high mobility environments unless the channel prediction is severely inaccurate. To alleviate the implementation problem with the use of Wiener predictors, we have proposed a grouped MMSE prediction scheme. The simulation results show that the proposed scheme can provide near optimum performance without implementation complexity problem.

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Table 1. Simulation condition.

Index	Value	Index	Value
Carrier freq.	5.8 GHz	Number of sub-carriers	2048
Cell radius	2.5 km	Packet size (N_t, N_f)	(64,8)
Guard interval	5 μ sec	Pilot spacing (d_t, d_f)	(8,4)
Symbol duration (T_s)	20.48 μ sec	Pilot pattern	Rectangular
Bandwidth	100 MHz	Doppler effect	Jakes' model
Duplex	FDD	Power delay profile	Flat fading

Table 2. Computational complexity.

type	Multiplication /symbol	Matrix inversion	Sample correlation
Wiener (U=5)	5	5 by 5	Inter-symbol
Grouped MMSE (U=5)	5	5 by 5	Inter-group
Wiener (U=51)	51	51 by 51	Inter- symbol

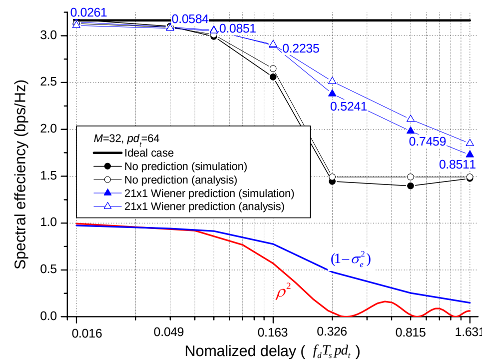

Fig. 1. Spectral efficiency with predicted channel gain when $\overline{\gamma}$ = 8dB.

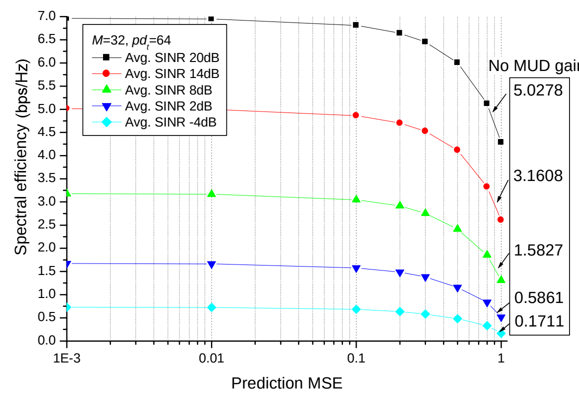

Fig. 2. Spectral efficiency due to prediction error.

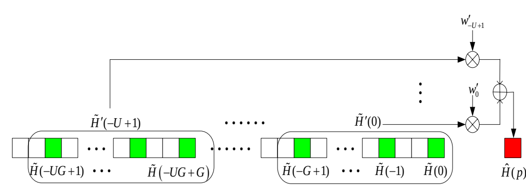

Fig. 3. Block diagram of the grouped MMSE prediction scheme.

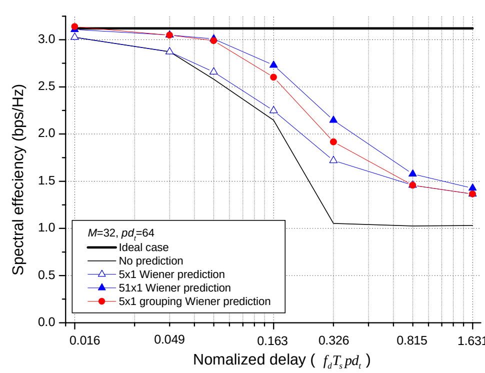

Fig. 4. Performance with the use of the grouped MMSE predictor when $\overline{\gamma}$ = 8dB .